Earth's Energy Balance for Clear, Cloudy and All-Sky Conditions

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Abstract

The researchers have published several studies on the radiation fluxes based on measurement data banks and radiative transfer models. The author has used available flux values and different methods to obtain the total of Earth's energy balances for clear, cloudy and all-skies. The calculation methods include balance equations, spectral calculations and the cloudiness factor in combining energy fluxes of three sky conditions. A new idea has been introduced that the surface albedo flux is partially absorbed in cloudy conditions, as with incoming shortwave radiation. The atmospheric albedo fluxes have been calculated separately for cloud reflection and air particles. Also the atmospheric absorption has been divided into cloud and clear air absorption fluxes.

Keywords

Earth's Energy Balance; Clear Sky; Cloudy Sky; All-Sky.

Introduction

General

Since the late '80s, comprehensive satellite measurements have been available for producing shortwave (SW) and longwave (LW) radiation data which have been utilized in calculating Earth's global energy budget. Rossow and Zhang (1995) produced a list of SW and LW radiation fluxes for clear, cloudy and all-sky atmospheres. The analyses were based on the data and results obtained from the climatology projects ISCCP (International Satellite Cloud Climatology Project) and ERBE (Earth Radiation Budget Experiment) and other sources.

Kiehl and Trenberth (1997) introduced one of the first comprehensive global energy budgets of Earth, and utilized mainly the ERBE data, the results of the earlier published analyses by other researchers and their own radiation flux calculations. Zhang et al. (2004) reconstructed the radiation flux values reported in the earlier paper by Rossow and Zhang (1995), as well used the newer data sets (Flux Data = FD) available from the ISCCP project and NASA Goddard Institute for Space Studies (GISS) radiative transfer models.

Raschke et al. (2005) published results that were also based on the ISCCP flux data producing the basic radiative fluxes. Bodas-Salcedo et al. (2008) carried out what was likely the most comprehensive analysis of the surface radiation fluxes to date, based on the ISCCP and BSRN (Baseline Surface Radiation Network) data comparing the measured data against HadCEM1 (Hadley Centre Global Environmental Model) results.

Trenberth et al. (2009) improved Earth's budget analysis of Kiehl and Trenberth (1997) utilizing the data and results obtained from the following climatology projects (among other sources): ERBE, CERES (Clouds and the Earth's Radiant Energy System), ISCCP, HOAPS (Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data), JRA (Japanese reanalysis), NRA (NCEP-NCAR reanalysis; NCEP (National Center for Environmental Prediction), NCAR (National Center for Atmospheric Research).

Presentations of Earth's energy budgets are so far available only for all-sky conditions. Some radiation fluxes are available for clear and cloudy skies but not for comprehensive energy budgets. This study's goal is to present the clear, cloudy and all-sky energy budgets for Earth. The calculations will be based on the latest published radiation fluxes, emitted/absorbed radiation fluxes based on spectral calculations and other mathematical analyses. The procedure has been to use the latest studies in the cases where they are found to be the most reliable solution.

Clear and cloudy sky conditions are challenging because a final balance cannot be reached in the real conditions of Earth. There are slightly different definitions for clear, cloudy and all-sky conditions. In this study, the available flux values of clear and cloudy-skies are from Zhang et al. (2004) and that is why these definitions do not need further analysis.

Symbols and Definitions

Table 1 includes all the symbols, acronyms and definitions used repeatedly in this paper. All the flux values are in the unit W/m^2, and therefore this unit is not always specified in this text.

TABLE 1 LIST OF SYMBOLS, ABBREVIATIONS AND DEFINITIONS

GH	Greenhouse
SW	Shortwave radiation
LW	Longwave radiation
TOA	Top of the atmosphere
ATM	Atmosphere
SFC	Surface
SWin	Incident solar radiation flux at TOA
Ra	Reflected Rs flux into space, Ra = Rs-Sr
Rc	SW flux reflected by clouds
Rp	SW flux reflected by air
Rt	Total reflected SW flux into space
Rs	SW flux reflected by the surface
Sa	Total SW flux absorbed in the atmosphere
Sb	Incoming SW flux absorbed by clear air
Sc	Incoming SW flux absorbed by clouds
Sd	Incoming SW flux reaching the surface
Si	Total incoming SW absorption flux by the atmosphere
Sr	SW flux of Rs flux absorbed by cloudy sky
Ss	SW flux absorbed by the surface
Sx	Incoming SW flux (Sx = SWin-Rc-Rp)
Ac	Upward LW surface flux absorbed by clouds
Ag	Upward LW surface flux absorbed by GH gases
Ec	Upward LW flux emitted by clouds
Ed	Downward LW flux emitted by the atmosphere
Eg	Upward LW flux emitted by the cloudless atmosphere
Es	Total LW flux emitted by surface (Es=Ac+Ag+Eu)
Eu	LW surface flux transmitted into space
T	Thermal flux
L	Latent heat flux
OLR	Outgoing LW radiation flux at TOA
NSR	Net incoming SW flux (NSR = SWin – Rt)
ASR	SW flux absorbed by the atmosphere and surface
Bs	Balance value of the surface
Ba	Balance value of the atmosphere

Clear sky is indicated by the subscript$_b$, cloudy atmosphere by the subscript$_o$, and all-sky atmosphere by the subsript$_a$.

Shortwave Energy Fluxes

The researchers have concentrated on the all-sky cases, and the latest reported values are almost identical. Table 2 summarizes the SW fluxes as selected and analysed in this study. Zhang et al. (2004) and Raschke et al. (2005) have found exactly the same SWin (342). Loeb et al. (2009) have analysed ERBE, CERES, ISCCP-FD, and GEWEX SRB (Global Energy and Water Cycle Experiment Surface Radiation Budget) data. The average value of 6 fluxes of a 5 years period gives OLR_b = 289, which is also the author's selection and therefore the clear sky value Rt_b is 53.0. Rt_o value 120 is from Zhang et al. (2004), which gives NSR_o = 342 – 120 = 222. The OLR_a values range from 233 to 240, depending on the source (Rossow and Zhang, 1995; Kiehl and Trenberth, 1997; Zhang et al., 2004; Raschke et al., 2005; Trenberth et al., 2009; Loeb et al., 2012, Stephens et al., 2012). The recent study of Loeb et al. (2009) used the CERES data and they have calculated that OLR_a is 239.6 and Rt_a is 99.5 W/m^2. Because there has been an imbalance in both SW and LW TOA values based on the satellite data, the author has used the value of 236.5, which is the same as calculated by Miskolczi (2010a). In order to close the SW budget to be 236.5 for all-sky, the Rt_a must be 105.5, which is close to 105.7 reported by Zhang et al. (2004).

The values for Ss, Rs and Sd in Table 2 for different skies are from Zhang et al. (2004), except Ss_a = 165.5, which is the average value of two sources (Zhang et al., 2004; Bodas-Sadcedo et al., 2008). Raschke et al. (2005) have reported almost the same values. The total absorbed SW flux can be calculated at TOA or using absorption values at surface and in the atmosphere. Keeping the absorbed values the same as the NSR values, the total atmospheric absorption fluxes can be calculated: Sa_b = 289 - 220 = 69, Sa_o = 222.0 - 150.0 = 72.0, and Sa_a = 236.5 - 165.5 = 71.

When the incoming solar light transmits through the atmosphere, air molecules cause Rayleigh scattering. When the light meets clouds, it may be reflected (sent backward), absorbed, scattered by water droplets according to the Mie mechanism or transmitted through. Rayleigh scattering enhances shorter wavelengths, causing the blue sky, and producing an almost symmetrical deflection pattern. Mie scattering is practically independent of wavelength, and it produces more deflections in the same direction as the incoming light-beam path (mainly in the Nadir direction). Essential features of both scattering mechanisms and reflection are that the light changes its direction but keeps its original wavelength and attenuation because the collisions of photons are elastic (McCartney, 1976).

In cloudy and all-sky conditions, the reflected SW radiation by the surface Rs must transmit partially or totally through the clouds, and it has the same options as by the incoming light, meaning that some part of it will be absorbed in the same way that the downward SW radiation from the sun is absorbed by clouds. The absorption in clouds is a complicated phenomenon, where the main factors are cloud optical thickness,

mean free path of the photons, the concentration and size distribution of water droplets and aerosols (Kondratyev et al., 1998). The direction of the light beam (upward or downward) in the absorption process has no effect. Because the earth has a spherical shape, even the incoming light has a large variety of encountering angles with absorbing elements, and this variety increases due to Mie scattering inside clouds. The absorption of SW flux in the atmosphere has been used in radiative transfer models but it seems that this phenomenon has been omitted in the earlier balance calculations by other researchers. The absorption of reflected SW flux Rs by GH gas molecules can be neglected because the absorption must be nearly saturated as it transmits through the atmosphere.

The term albedo can be used in vague ways. Pinty et al. (2005) have given the exact definition: albedo at some level z of a geophysical system is defined as the ratio between the upward flux density or irradiance exiting that particular level and the downward flux density impinging on that same level z. Therefore, in the global radiation flux presentations, the surface albedo flux is the reflected flux above the surface and not at TOA. This is clearly defined for example in the paper of Zhang et al. (2004).

The total reflected SW radiation (=albedo) is the sum of reflected SW fluxes by the surface (reduced by cloud absorption, Ra=Rs-Sr) by aerosols and by clouds:

$$Rt = Ra + Rc + Rp \tag{1}$$

Zhang et al. (2004) have reported Ra_b = 29.8 W/m^2 for the surface albedo. The clear sky aerosol albedo Rp_b is thus 53.0 – 29.8 = 23.2 W/m^2. As there are no reported values for Rp_o and Rp_a, the author has estimated these values. According to Davies and Molloy (2012), the average global cloud top height is 7.3 km. Above this altitude is 38% of the molecular mass of the atmosphere. Assuming that the reflection by aerosols/air is linearly dependent upon the amount of molecules and that reflected radiation by air cannot take place in clouds or below them, the Rp_o can be estimated to be 0.62 * Rp_b = 14.4 W/m^2. Using Eq. (2) and assuming 66% average cloudiness (ISCCP, 2012), Rp_a would be 17.4 W/m^2.

There are no measured or calculated values available for fluxes Rc reflected by clouds. The author has calculated the Rc values and the absorption fluxes Sr by the iteration method. Two iterations were needed, and only the final results are shown in Table 2. Sx represents the downward flux, which is calculated by subtracting the values of reflection fluxes Rc and Rp from SWin. The clear sky absorption-% = 100 * Sb_b/Sx_b = 100 * 69/318.8 = 21.6. This percentage has been used in calculating the air absorption for cloudy and all-sky conditions; and the values are Sb_o = 52.4 and Sb_a = 56.1.

The Sc values can be calculated as differences between the Si values and Sb values, which produces the values Sc_o = 18.0 and Sc_a = 13.6. The cloudy sky absorption-% = 100 * Sc_o/Sx_o = 100 * 18.0/242.4 = 7.43, and the all-sky absorption-% = 100 * Sc_a/Sx_a = 13.6/259.8 = 5.25. Using these absorption-% values, the absorption fluxes Sr of reflected flux Rp can be calculated. The results are Sr_o = 1.6 and Sr_a = 1.3. The values for Rc can be calculated according to equation (1) keeping the measured values of Rt for different skies in Table 2. The incoming SW Sd flux values in Table 2 can be compared to the measured values by Zhang et al. (2004) and the differences are below 0.6% for each sky conditions.

TABLE 2 SHORTWAVE RADIATION FLUX VALUES IN W/m^2

Shortwave radiation budget	**Abbr.**	**Clear**	**Cloudy**	**All-sky**	**Uncertainty**
Incident solar radiation flux at TOA	SWin	342.0	342.0	342.0	4 – 6[3]
Total reflected SW radiation flux into space	Rt	53.0	120.0	105.5	5 -10[1]
SW flux reflected by clouds	Rc	0.0	85.40	65.4	7 - 15[3]
SW flux reflected by air	Rp	23.2	14.4	17.4	7 - 15[3]
Incoming SW flux (Sx = SWin-Rc-Rp)	Sx	318.8	242.4	259.2	5 - 10[1]
Incoming SW flux absorbed by clear air	Sb	69.0	52.4	56.1	5 – 10[3]
Incoming SW flux absorbed by clouds	Sc	0.0	18.0	13.6	5 - 10[3]
Total incoming SW absorp. flux by the atm.	Si	69.0	70.4	69.7	5 - 10[3]
SW flux of Rs flux absorbed by cloudy sky	Sr	0.0	1.6	1.3	0.3 – 0.9[3]
Total SW flux absorbed in the atmosphere	Sa	69.0	72.0	71.0	5 - 10[3]
Incoming SW flux reaching the surface	Sd	248.9	171.8	189.5	10 - 15[1]
SW flux reflected by the surface	Rs	29.8	21.8	24.0	5 -10[2]
Reflected Rs flux into space. Ra = Rs-Sr	Ra	29.8	20.2	22.7	5 -10[2]
SW flux absorbed by the surface	Ss	220.0	150.0	165.5	10 - 15[1]
Net incoming SW flux (NSR = SWin – Rt)	NSR	289.0	222.0	236.5	5 - 10[1]
SW flux absorbed by the atm. and surface	ASR	289.0	222.0	236.5	5 - 10[1]

Over the years, there has been the so-called anomalous absorption problem, because the measured solar absorptions for cloudy skies have produced values that exceed the radiative transfer model values. Ackerman and Stokes (2003) and Ackermann et al. (2003) have concluded that this difference can be reduced to 8-14%. This problem is beyond the scope of this study.

There are no reported values for cloud and aerosol albedo so far. The probable reason is that the measurement arrangements are not easy to be executed, because it is difficult to separate the origin (surface, cloud or aerosols) of SW upward radiation. Raschke et al. (2005) have estimated that 50% of planetary all-sky albedo can be attributed to clouds, and Ahrens and Samson (2010) have estimated that cloud albedo is 60%. The value 65.4 W/m² of Rc_a calculated in this study is 62% of the total all-sky planetary albedo.

The uncertainty values in Table 2 marked by superscript[1] are from Zhang et al. (2004), superscript[2] are from Stephens et al. (2012) and superscript[3] means that the uncertainty values have been calculated.

Longwave Radiation Budget

Longwave Radiation Calculation Basis

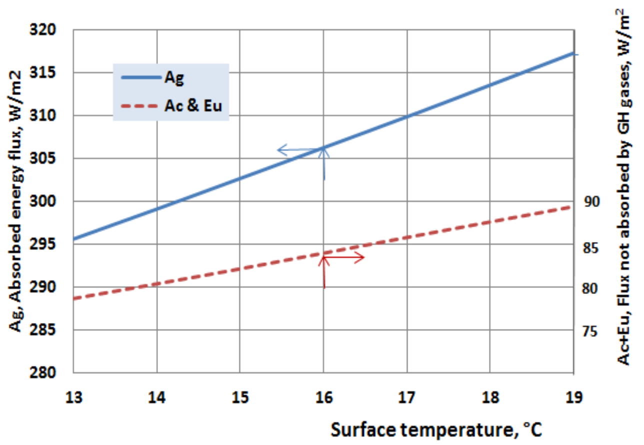

FIG. 1 THE EMITTED, ABSORBED (Ag) AND TRANSMITTED (Ac & Eu) FLUXES AS FUNCTIONS OF THE SURFACE TEMPERATURE IN THE AVERAGE GLOBAL ATMOSPHERE.

In the LW budget analysis, the author has used the latest reported values as the first priority, if they are available. The radiation emission values and absorption values by GH gases have been calculated utilizing the Spectral Calculator which is available on the Internet. This application is provided by Gats Inc. (2012), and it uses the Hitran database (2012) for GH gases. These calculations in the temperature ranging from 13°C to 19°C were carried out in the average global atmosphere having the following anthropogenic GH gas concentrations in the year 2005: CO_2 379 ppm, CH_4 1.774 ppm, and N_2O 0.319. Water content was the same as reported by Ellingson et al. (1991) and Miskolczi (2010b) which is 2.6 prcm (precipitated water in centimetres). The calculations were carried out for an air column up to 120 kilometres. The results are shown in Figure 1. More details of the calculation basis are available in the article by Ollila (2012).

There are not enough measured and analysed results of energy fluxes for clear and cloudy sky conditions. In calculating some of the missing values, Eq. (2) has been utilized.

$$(1-k) * F_b + k * F_o = F_a \qquad (2)$$

where F_b is the energy flux of the clear sky, F_o is the energy flux of the cloudy sky, F_a is the energy flux of the all-sky, and k is the all-sky cloud cover factor. Kiehl and Trenberth (1997) have used a k value of 0.62, Raschke et al. (2005) have found higher values from 0.67 to 0.74. The k value in this study is 0.66 because it is the average value according to ISCCP (2012) during the last 10 years. Clouds vary a lot with respect to the optical properties because the fragmented clouds do not have the same optical effects as the thick clouds. One could criticize this choice if the fluxes actually follow this relationship. Bellouin et al. (2003) have used the same kind of equation in combining the results of different skies. The LW budget analysis results are depicted in Table 3.

The "Surface in" Budget

The all-sky value for Ed_a 344.7 W/m² is from Zhang et al. (2004). From the same source is Ed_o value 359 W/m² and Ed_b = 313 W/m². Rossow and Zhang (1995) have found Ed_b = 323 W/m². The average of these two Ed_b values is 318 W/m², and the author has used this value, which is almost the same as 319 W/m² calculated by Stephens et al. (2012).

Ss_b should be theoretically the same as ASR_b = NSR_b = 289 W/m², but in real climate conditions, the balance value for OLR_b cannot be reached. The basic reason is in the dynamics of the atmosphere. The difference of 30W/m² (= 289-259) is due to the fact that the atmosphere does not have enough time to reach a new steady state (equilibrium) from the all-sky conditions in response to the incoming solar irradiance stepwise change from the all-sky value 236.5 W/m² to 289 W/m². An Ss_b value of 190 W/m² has been used in this study because it produces the correct balance value at TOA: $Ss_b + Sb_b$ = 190 + 69 = 259 = OLR_b. The value of Ss_o can be calculated in the same way: Ss_o = 226.8 – 72.0 = 154.8.

TABLE 3 THE SUMMARY OF ERTH'S ENERGY BUDGETS FOR CLEAR, CLOUDY AND ALL-SKIES. THE VALUES ARE IN W/m^2

		Pseudo-balance			**True balance**		**Uncertainty**
Surface in	**Abbr.**	**Clear**	**Cloudy**	**All-Sky**	**Clear**	**Cloudy**	
SW flux absorbed by surface	Ss	190.0	154.8	165.5	220	150	5 - 10[1]
Downward LW flux emitted by the atm.	Ed	318.0	359.0	344.7	378	300	10 - 15[3]
SFC-balance	**Bs**	**508.0**	**513.8**	**510.2**	**598**	**450**	11 – 22[3]
Surface out							
Thermals	T	26.4	27.3	24.6	33	14	5 – 10[2]
Latent heat flux	L	87.5	90.3	90.0	120	53	5 – 15[2]
LW surface flux transmitted to space	Eu	83.2	0.0	28.5	67	0	3 - 7[3]
LW surface flux absorbed by clouds	Ac	0.0	84.0	55.2	0	83	3 - 7[3]
LW surface flux absorbed by GH gases	Ag	310.9	312.2	311.9	378	300	3 - 7[3]
SFC-balance	**Bs**	**508.0**	**513.8**	**510.2**	**598**	**450**	11 – 22[3]
Atmosphere in							
Incoming SW flux absorbed by clear air	Sb	69.0	52.4	56.1	69	53	5 – 10[3]
Total SW flux absorbed by clouds	Sc+Sr	0.0	19.6	14.9	0	19	5 – 10[3]
Thermals	T	26.4	27.3	24.6	33	20	5 – 10[2]
Latent heat flux	L	87.5	90.3	90.0	120	47	5 – 15[2]
LW surface flux absorbed by clouds	Ac	0.0	84.0	55.2	0	83	3 - 7[3]
LW surface flux absorbed by GH gases	Ag	310.9	312.2	311.9	378	300	3 - 7[3]
ATM-balance	**Ba**	**493.8**	**585.8**	**552.7**	**600**	**522**	11 - 23[3]
Atmosphere out							
Upward LW flux emitted by the atm.	Eg	175.8	167.0	168.5	222	163	7 - 15[3]
Upward LW flux emitted by clouds	Ec	0.0	59.8	39.5	0	59	5 – 10[3]
Downward LW flux emitted by the atm.	Ed	318.0	359.0	344.7	378	300	10 - 15[3]
ATM-balance	**Ba**	**493.8**	**585.8**	**552.7**	**600**	**522**	11 - 23[3]
TOA							
Upward LW flux emitted by the atm.	Eg	175.8	167.0	168.5	222	163	7 - 15[3]
LW surface flux transmitted to space	Eu	83.2	0.0	28.5	67	0	3 - 7[3]
Upward LW flux emitted by clouds	Ec	0.0	59.8	39.5	0	59	5 – 10[3]
OLR	**OLR**	**259.0**	**226.8**	**236.5**	**289**	**222**	5 - 10[1]

The "Surface out" Budget

According to Zhang et al. (2004), the Es values are Es_b = 394.1, Es_o = 396.3, and Es_a = 395.6. These values correspond to the following black surface temperatures: 15.6°C, 16.0°C, and 15.9°C. The transmitted and absorbed values can be calculated carrying out the spectral absorption calculations in the average global atmosphere. The results are: Eu_b = 83.2, Ac_o = 84.0, and $Eu_a + Ac_a$ = 83.7. Eq. (2) can be used to calculat Eu_a and Ac_a, assuming that 66% of Es_a will be absorbed by clouds (=Ac_a) and the rest (=Eu_a) is transmitted into space through the atmospheric window. This calculation gives 55.2 W/m^2 for Ac_a and 28.5 W/m^2 for Eu_a.

Costa and Shine (2012) have carried out radiation absorption calculations using the line-by-line method and 3D climatologies and their results are 66 W/m^2 for Eu_b, 22 W/m^2 for Eu_a, and the clear sky value without water vapour continuum 100 W/m^2. This latter value could mean that the water content of the atmosphere is smaller than the real global average value of 2.6 prcm. As noticed by Costa and Shine (2012) Trenberth et al. (2009) do not have clear calculation basis for Eu_a. The difference between Eu_a values (28.5 versus 22) of this paper and Costa and Shine (2012) is due to the different radiation calculation methods (water vapour continuum algorithm).

The surface budget for the all-sky can be written in the form $T_a + L_a = Ss_a + Ed_a - Es_a$. There are several flux values available, and the following references are presented here for $T_a + L_a$: Zhang et al. (2004) 114 W/m^2, Raschke et al. (2005) 115 W/m^2, Bodas-Salcedo et al. (2008) 117 W/m^2, and Stephens et al. (2012) 112±15 W/m^2. The latent heat fluxes (L_a) and thermal fluxes (T_a) vary quite a lot in different studies. Kiehl and Trenberth (1997) have listed 13 studies, and the values range from 78 to 88 W/m^2 for L_a and from 16 to 27 W/m^2 for T_a.

The energy balance of this study can be closed, if $T_a + L_a$ is 114.6 W/m^2, which is the average value of the all referred values above. Stephens et al. (2012) have analysed the latest satellite observations and they have concluded that the global precipitation has increased to 88±10 W/m^2. Based on this finding, the author's selection is 90.0 W/m^2 for L_a, and 24.6 W/m^2 for Ta because these values keep the same relationship (88/24) as reported by Stephens et al. (2012). The higher value

of latent heat flux is an important improvement in closing the energy balance at surface, because there has been a mismatch of energy fluxes in all energy balance presentations.

The values of T_b, T_o, L_b, and L_o are obtained by closing the balances of Ba_b and Ba_o in an exact way and keeping the relationship between T_b/L_b and T_o/L_o the same as in all sky conditions.

The "Atmosphere in" Budget

Actually, all the energy fluxes are already available from the "surface out" budget and SW radiation budget.

The "Atmosphere out" Budget

The balance value of Ba_b is 493.8. Because the Ed_o is 318 W/m², the Eg_o = 493.8 – 318.0 = 175.8 W/m². The missing radiation values can be calculated by solving the following equations:

$$Eg_o + Ec_o = Ba_o - Ed_o = 585.8 - 359 = 226.8 \quad (3)$$

$$Eg_a + Ec_a = Ba_a - Ed_a = 552.7 - 344.7 = 208.0 \quad (4)$$

$$0.34 * 175.8 + 0.66 * Eg_o = Eg_a \quad (5)$$

$$0.66 * Ec_o = Ec_a \quad (6)$$

These values satisfy the above equations: Eg_o = 167.0 W/m², Eg_a = 168.5 W/m², Ec_o = 59.8 W/m², and Ec_a = 39.5 W/m².

The TOA Budget

Radiation fluxes do not need to be calculated because they are available from "atmosphere out" and "surface out" budgets. The balance values for different skies are: OLR_b = 259 W/m², OLR_o = 226.8 W/m², and OLR_a = 236.5 W/m². The obtained values prove that the calculations have been carried out correctly because the SW input energy fluxes are the same as LW output fluxes at TOA: $Ss_b + Sc_b = ASR_b = OLR_b$, $Ss_o + Sc_o = ASR_o = OLR_o$, and $Ss_a + Sc_a = ASR_a = OLR_a$.

Summary and Check of the Budgets

A graphical presentation of Earth's budget is depicted in Figure 2.

The analytical methods for the 33 LW energy fluxes of Earth can be summarized as follows: measured values 8, spectral calculations 8, absorption calculations 4 (Sb, Sc, Sr), balance calculations 6, combined calculations of Eq. (2) and balance values 6, and cloudiness factor Eq. (2) 1 (Eu).

The calculated clear air absorption flux values of Sb can be checked by analysing the upward radiation fluxes (Eg) emitted by the clear atmosphere. There are two input radiative fluxes, Sb and Ag, which play the main roles in creating the upward flux Eg. Thermals and latent heat fluxes can change the atmospheric temperatures, but their effects are very insignificant when considering the small changes of T and L between different atmospheres. The Ag values of different skies are also almost the same.

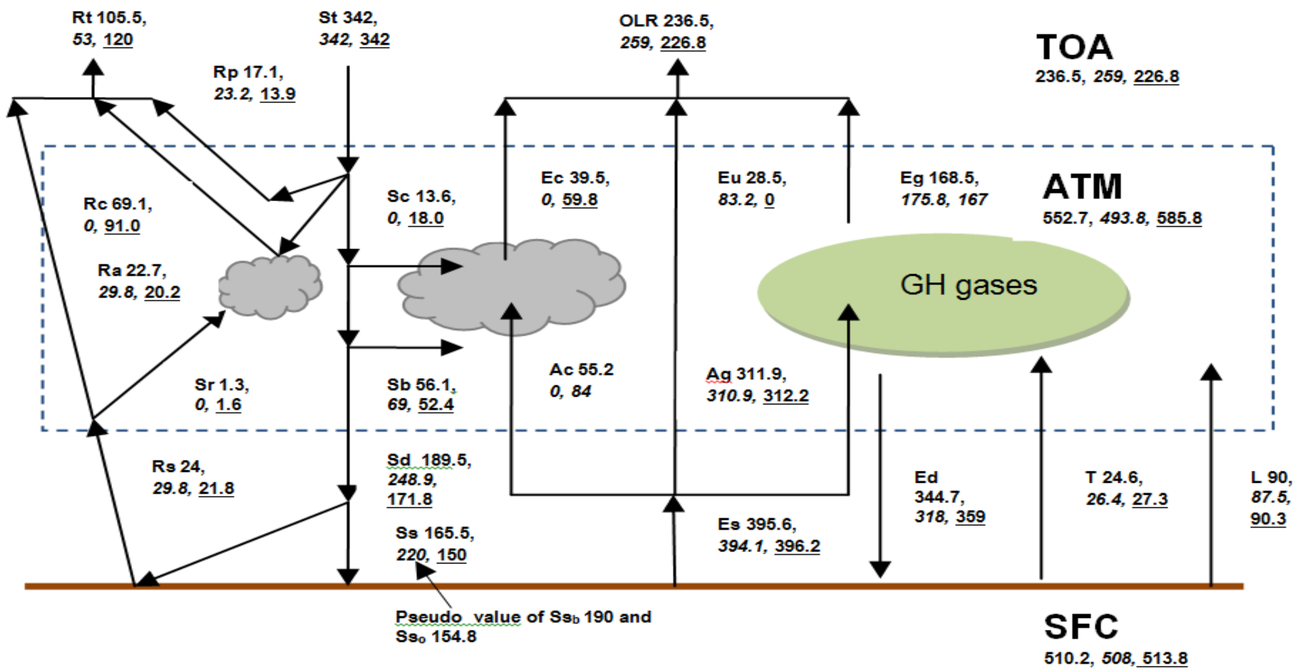

FIG. 2 GRAPHICAL PRESENTATION OF EARTH'S ENERGY BUDGETS. THE FIRST VALUE OF EACH FLUX IS FOR ALL-SKY, THE SECOND VALUE IS FOR CLEAR SKY (ITALICS), AND THE THIRD VALUE IS FOR CLOUDY SKY (UNDERLINED)

The first estimate therefore is that the changes in Eg of different skies are caused by the Sb fluxes which are SW fluxes absorbed by clear air. The relationship in the clear sky between $Sb_b/(Sb_b + Ag_b)$ is 69/379.9 = 0.1816. Using this relationship gives the results that Sb_b produces upward flux of 31.9 and Ag_b produces 143.9 – the sum being 175.8 = Eg_b. These results mean that by multiplying Sb_b by the factor 0.463, the value 31.9 can be produced. It can be estimated that Ag_o and Ag also produce the same flux of 143.9. The Sb_o flux = (167.0 – 143.9)/0.463 = 49.9 W/m², which is 4.8% smaller than the value 52.4 as calculated based on the Sx_o flux absorption. In the same way, the Sb_a flux = (169.0 – 143.9)/0.463 = 54.2 W/m², which is 3.4% smaller than the value 56.1 calculated on the Sx_a flux absorption. This calculation basis is rather sensitive for small errors in Eg values. The Sb_a calculated according to Eq. (2) gives the value 58.0, which differs by only 3.4% from the 56.1 calculated on the Sx_a flux basis.

The author has not included the ocean heating into the energy balance like Trenberth et al. (2009) and Stephens et al. (2012) who have calculated this flux to be 0.9 W/m² and 0.6 W/m². According to oceans temperature data banks, the temperatures stopped to increase after 1998 as it can be seen in Figure 3 (EPA, 2013). According to Loehle (2009) the oceans started even to cool after 2002.

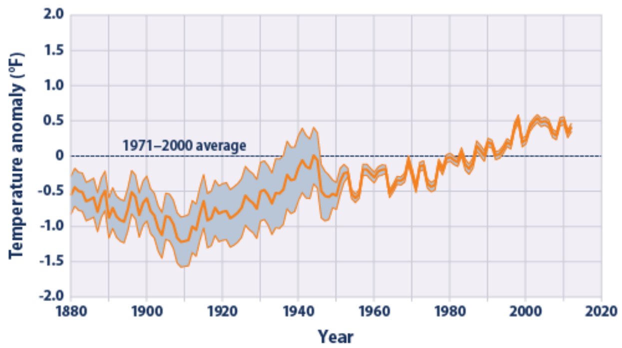

FIG. 3 AVERAGE GLOBAL SEA SURFACE TEMPERATURE 1880-2012 ACCORDING TO UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (EPA, 2013). THE DATA IS ORIGINALLY FORM NOAA. THE SHADED BAND SHOWS THE RANGE OF UNCERTAINTY IN THE DATA

The uncertainty values in Table 3 are marked and estimated in the same way as in Table 2. The OLR uncertainty values may be illogical if compared to the flux uncertainty values, which the overall flux OLR is built up, but the OLR values are based on the measured values and not on the sum of individual fluxes.

True Energy Balance of Longwave Radiation Budget

The true energy balance calculations for clear and cloudy skies can be carried out, but the calculation bases are more uncertain because only the SW flux values are available.

These calculations can be started from the TOA value of the clear sky, which is 289 W/m² (the sum of Eg and Eu). Miskolczi and Mlynczak (2004) have calculated Ed and Eg fluxes as functions of the surface temperature. The author has calculated the Eu and Es as the functions of the surface temperature utilizing the Spectral Calculator and different atmospheres of the Earth (Ellingson et al.. 1991). These results are depicted in Figure 4.

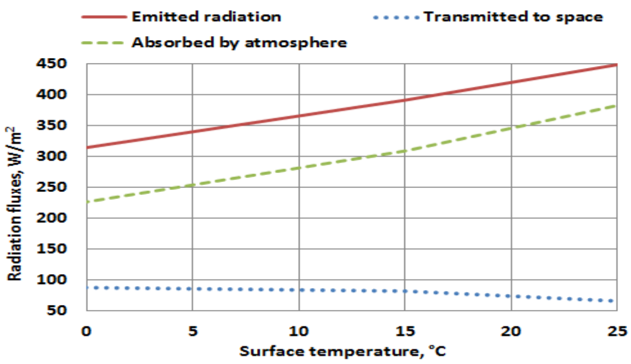

FIG. 4 EMITTED, TRANSMITTED AND ABSORBED RADIATION FLUXES AS FUNCTIONS OF THE SURFACE TEMPERATURE. THE GLOBAL ATMOPSHERIC ZONES HAVE BEEN UTILIZED AS EXPLAINED BY OLLILA (2012) BUT AT TEMPERATURE 15 °C, THE AVERAGE GLOBAL ATMOSPHERE HAS BEEN USED

The temperature that produces the Eg_b value of 222, Eu_b value of 67, and the Ag_b value of 378, is 24.5°C. In clear sky conditions Ed_b = Ag_b (with 3% maximum deviation) according to Miskolczi (2010a), which has been confirmed in hundreds of atmospheric clear sky structures. This requires a balance situation in the atmosphere. In the pseudo-balance situation, these two fluxes are not equal, as confirmed by the real measurements. The thermal flux and the latent heat fluxes are calculated on the same basis as before.

In true balance conditions, the equation (2) is not applicable, because the OLR values are not in linear dependency anymore. The OLR values satisfy the equation (7)

$$0.216 * 289 + 0.784 * 222 = 236.5 \quad (7)$$

The cloudy sky surface temperature can be calculated according to Eq. (7), giving the value of 13.5°C. Using this temperature, Ag_o is 300 W/m² and Ac_o is 83 W/m². Also in this case, Ed_o = Ag_o = 300 W/m². The other fluxes have been calculated on the same basis as before; and the results are shown in Table 3.

Discussion and Conclusions

In this study, Earth's energy balances for clear and

cloudy skies have been calculated and the all-sky balance has been updated according to the latest SW and LW flux analyses.

Also a new radiation flux has been introduced based on the assumption that the reflected radiation from the surface has to transmit through clouds in cloudy and all-sky conditions up into space. The absorption for this radiation flux can be estimated to be the same percentage as for the downward SW radiation from the sun. These absorption fluxes are very small in size: 1.6 W/m^2 for cloudy sky and 1.3 W/m^2 for all-skies.

The albedos of clouds and aerosols (air) have been calculated for cloudy and all-skies, based on the estimate of the relationship between the molecular mass of the atmosphere being above the average cloud top height and below that height.

The author has also calculated the numerical values for clear air absorption fluxes. The fluxes are Sb_o = 52.4 W/m^2 for cloudy sky and Sb_a = 56.1 W/m^2 for all-skies. Using these flux values, the total absorption caused by clouds can be calculated; the flux values are 19.6 W/m^2 for cloudy sky and 14.9 W/m^2 for all-sky. These fluxes together with fluxes reflected by air and by clouds explain why the total absorption fluxes of different skies are almost the same: 69 for clear sky, 72 for cloudy sky, and 71 for all-skies. Wild et al. (1998) have estimated that the all-sky atmospheric absorption flux would be 85.5 W/m^2, but this is 20.4% higher than the value based on the measurement results of Zhang et al. (2004). The clear air absorption values have also been calculated based on the upward fluxes emitted by the atmosphere, and the results have been almost the same (less than a 5% difference).

When compared to the Earth energy balance reported by Trenberth et al. (2009), three major differences can be found. The first difference is in the downward LW flux: in this study, the value is 344.7 W/m^2, while Trenberth et al. (2009) have used the value 333 W/m^2. Several studies of measurement data support value of this study (Rossow and Zhang, 1995; Zhang et al., 2004; Raschke et al., 2005; Bodas-Sadcedo et al., 2008; Stephens et al., 2012), ranging from 343-348 W/m^2. The second difference is in the value of SW flux absorbed by the surface. In this study, it is 165.5 W/m^2, which is also supported by the same studies as referred above for the downward LW flux ranging from 165-166.2 W/m2. Trenberth et al. (2009) gave a value of 161 W/m^2.

The third difference is caused by the differences in these two fluxes. The latest research results (Zhang et al. (2004) 114 W/m^2, Raschke et al. (2005) 115 W/m^2, Bodas-Salcedo et al. (2008) 117 W/m^2, and Stephens et al. (2012) 112±15 W/m^2) based on global data banks gave about the same size for the sum of latent heat and thermals which range from 112 W/m^2 to 117 W/m^2, with the most common latent heat values ranging from 80 to 88 W/m^2. In this study, the sum of latent heat and thermals is 114.6 W/m^2, and latent heat is 90 W/m^2, which leaves 24.6 W/m^2 for thermals. These two fluxes are close to the values presented by Stephens et al. (2012). This latent heat of 24.6 differs from the value of 17 W/m^2 presented by Trenberth et al. (2009). The value of thermals is based on the closing of the balance, and it is possible that errors in other fluxes cumulate in thermals. But in this case, the balance values should be reliably confirmed in many studies. As noted before, these differences in thermal and latent heat fluxes are caused by two fluxes absorbed by the surface: 344.7 + 165.5 = 510.2 versus 333 + 161 = 494. Thermals are difficult to calculate, but it is known that they cause a lot of heat to move from the equator zone to the polar zones, making temperatures more even.

For the clear and cloudy sky budget calculations, the SW input values for absorbed SW radiation have been those observed as OLR values. This is the only way to close the balance calculations, because the climate is in a dynamic state and cannot reach the balance value equal to the measured input value of SW radiation.

A special method applied is the assumption that the all-sky values can be calculated by summarizing the clear and cloudy sky values using the cloudiness factor of Earth, which is 66% in this study. In a total of eight cases, the calculations are based on combining totally or partially balanced equations with the cloudiness factor equation. In two fluxes, the only way is to use the cloudiness factor method. This kind of analytical method is in some degree theoretical, and it has been the only way to estimate these two theoretical extreme climate conditions because direct measurement values are not available.

The radiation fluxes of Ed (emitted atmospheric downward LW radiation) are evidence that the cloudiness factor is not merely a theoretical assumption based on the relationship between the three sky conditions. The measured values of the three sky conditions also satisfy Eq. (2), based on the utilization of the cloudiness factor. Further studies may establish whether this method has been sufficiently accurate.

Because the flux values of this study are mostly based on the other studies, the author has used the uncertainty values of Zhang et al. (2004) and Stephens

et al. (2012), if they are available. The author has evaluated the uncertainties of his own calculations.

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